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DESIGN AND DEMONSTRATION OF A HIGH-TEMPERATURE, DEPLOYABLE, MEMBRANE HEAT-PIPE RADIATOR ELEMENT

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ABSTRACT

Demonstration of a high-temperature, deployable, membrane heat-pipe radiator element has been conducted. Membrane heat pipes offer the potential for compact storage, ease of transportation, self-deployment, and a high specific radiator performance (kg/kW), for use in thermal rejection systems for space nuclear power plants. A demonstration heat pipe 8-cm wide and 100-cm long was fabricated. The heat pipe containment and wick structure were made of stainless steel and sodium utilized as the working fluid. The tests demonstrated passive deployment of the high-temperature membrane radiator, simulating a single segment in a flat array, at a temperature of 800 K. Details of test procedures and results of the tests are presented in this paper together with a discussion of the design and development of a full-scale, segmented, high-temperature, deployable membrane heat pipe.

NOMENCLATURE

A	Surface area, m^2
Q	Thermal power, W
ε	Normal total emissivity, dimensionless
σ	Stefan-Boltzmann constant, $5.67(10^{-8})$ $W/m^2\text{-}K^4$

Subscripts

hp	Heat pipe
vc	Vacuum chamber

INTRODUCTION

Future space missions and defense systems will require power supplies in the tens of megawatts range. At these power levels the mass of the power system is dominated by the thermal-rejection sub-system, which may be more than 80% of the total mass for a closed loop system, using conventional technology. As part of current programs for space nuclear power, the technology of light-weight, large-area, heat rejection radiators with operating temperatures of greater than 600 K is being investigated. Membrane heat pipes have been proposed as an advanced radiator concept capable of significantly reducing the system mass and volume. These systems are expected to operate maintenance free for a period of 7 to 20 years. Large area requirements have led to the development of deployable heat pipe structures for ease of transport to space. Current state-of-the-art radiator designs provide a specific mass in the range of 5 to 20 kg/m^2. Membrane heat-pipe designs, utilizing alkali metals as the working fluids and metal foil for containment, offer the potential for a specific mass of about 1.8 kg/m^2 and a mass-to-power ratio of approximately 0.04 kg/kW at 1000 K.

Self-deploying radiators may be used for various applications. In future space power systems such as in space defense, systems may be operated for short periods followed by long dormant periods. Under these conditions the heat pipes may be rolled-up for compact storage and shielding from space debris and micrometeroids between operating periods. Space radiators for continuously operating power systems may use self-deployable radiators without retraction capabilities. They may be rolled-up for compact storage during transportation in the launch vehicle and then passively deployed during initial system start-up. Passive deployment is achieved by the internal pressure developed as the working fluid is brought to operating temperature and thus requires no external power source or special purpose mechanism. This concept is shown in Fig. 1, where a flat array of membrane heat pipes, joined to form a sheet structure, is rolled into a cylindrical configuration for transport aboard the launch vehicle and unrolled in space to form the radiator surface.

HEAT PIPE DEVELOPMENT AND FABRICATION

A high-temperature, deployable, membrane heat pipe 100 cm long, with an 8-cm-wide radiator simulating a single segment in a flat array was fabricated and tested. Design operating temperature was 1000K. Because of the operating temperatures, metal foil was chosen for containment and sodium alkali metal as the working fluid. The containment and wick were made of 304 stainless steel. The membrane radiator containment material was 0.0127 cm thick stainless steel foil. The fluid distribution system consisted of a homogeneous slab wick structure. Two layers of 100X100-mesh stainless steel screen were cut on a bias and joined to develop the wick. The evaporator was fabricated stainless steel tubing. The heat input region was circular and the transition zone betwaen the heat input and foil condenser was tapered from a circular to an oolong cross-section as shown on the schematic in Fig.2.

Fabrication Procedure

The fabrication procedure was begun by cutting the 304 stainless steel foil into two rectangular sheets. Two strips of 100X100 mesh stainless steel screen (7.5-cm wide and 100-cm long) were cut on a bias to allow greater flexibility of the wick structure in the flexible condenser region. A series of spot resistance welds were used to join the two strips of screen to form the slab wick. The foil and wick were then chemically cleaned with a caustic solution. Joining the wick to one sheet of foil was

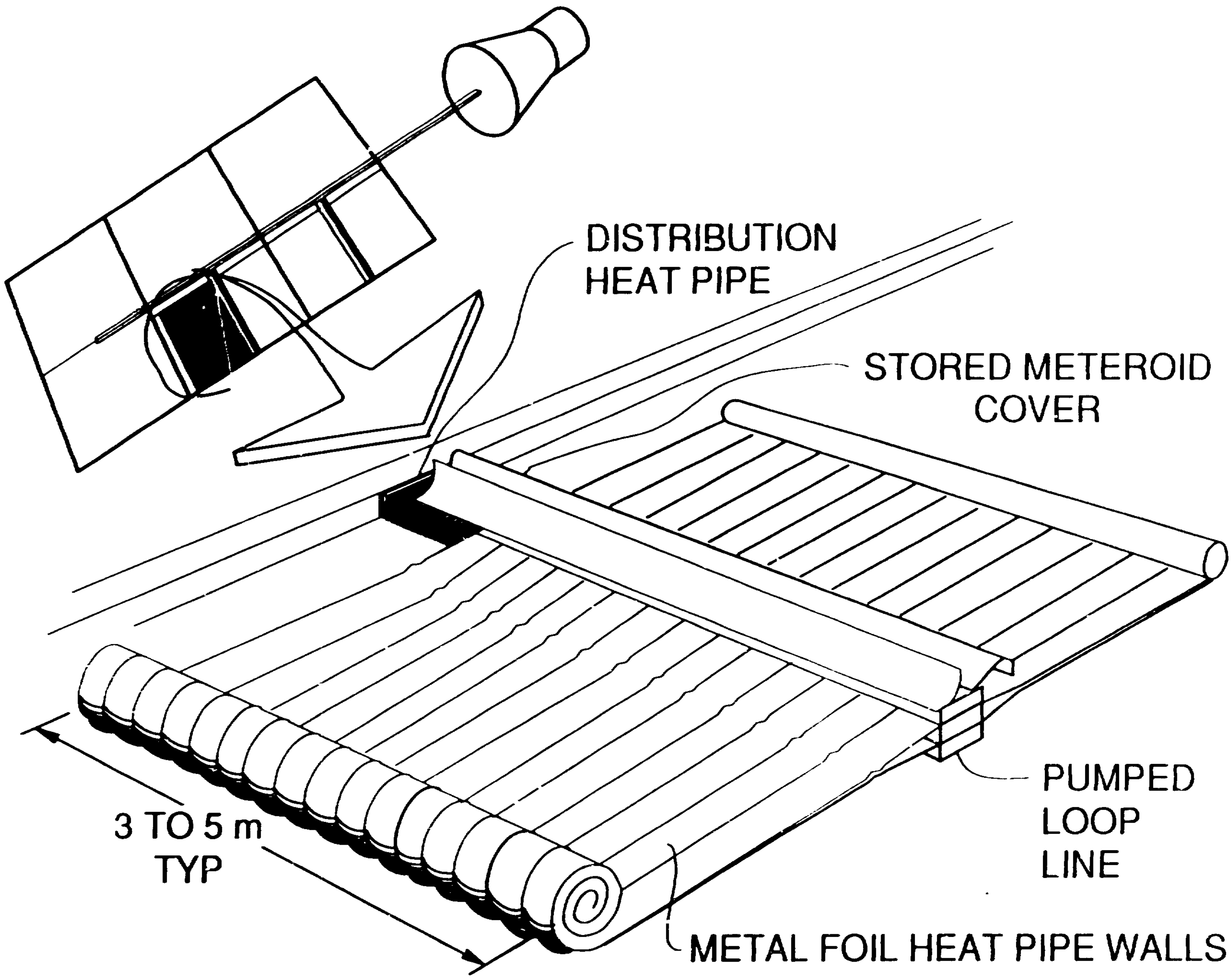

Figure 1: Schematic of a flat array of membrane heat-pipes.

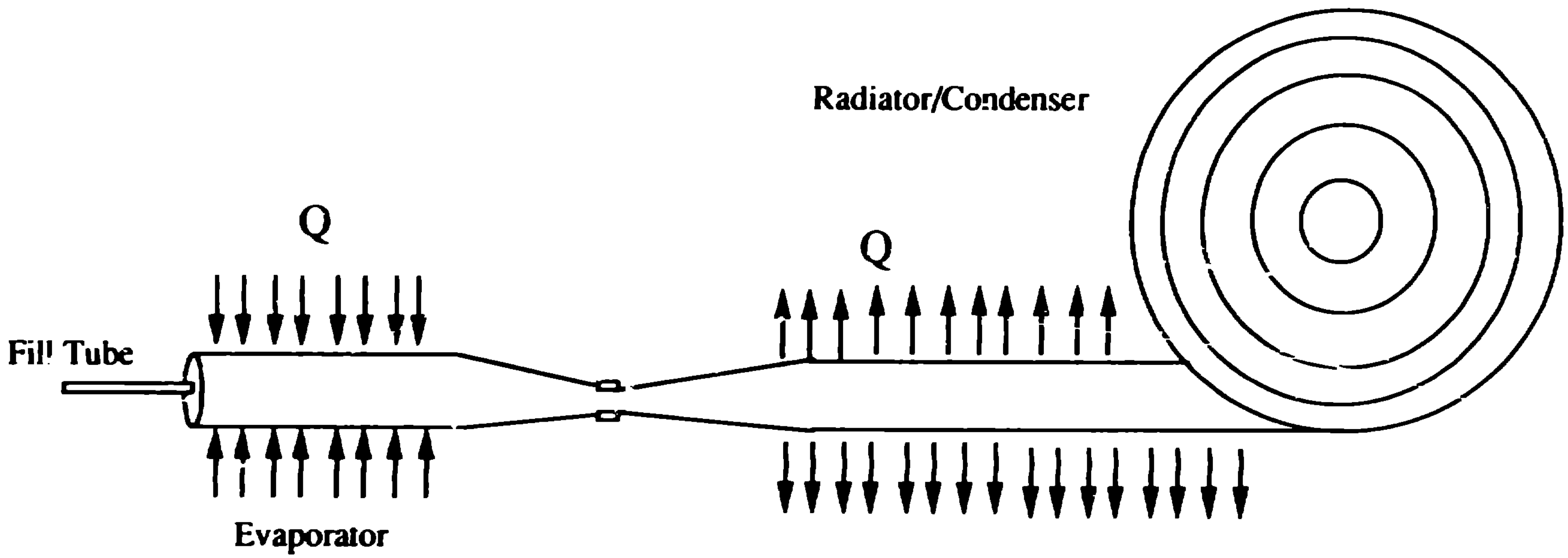

Figure 2 Schematic of demonstration heat-pipe radiator element

accomplished by resistance welding with a bench seam welder. The remaining sheet of foil was then joined to the foil/wick assembly by seam welding the two foil sheets along the edges to form the condenser envelope.

A 5.1-cm diameter stainless steel tube with a 0.0889 cm wall thickness was used for the evaporator. It was maintained circular at the heat input region for ease of rf-induction heating. The remaining tube length between the heat-input zone and the foil condenser was tapered from a circular to an elliptic cross-section to achieve a smooth transition to the foil condenser opening and thus reduce the amount of wrinkling of the foil in this region. A wire cage type structure was placed in the tube/foil-condenser cross-section interface to prevent the foil from being drawn into the evaporator while the heat pipe chamber was being evacuated. The foil condenser was joined to the thicker wall evaporator tube by fusion welding. The heat pipe was then leak checked with a helium diffusion leak detector. When the system was helium-leak tight, an end cap and fill tube were joined to the assembly.

The heat pipe was vacuum degased by furnace heating at a temperature of 1175 K for approximately one hour, and then charged with a pre-determined volume of sodium. The sodium was transferred to the heat pipe by distillation with the apparatus shown in the schematic on Fig.3. A photograph taken during distillation is shown in Fig. 4. The following operations were performed in sequence during the distillation process: 1) the heaters on the calibrated volume were brought to temperature allowing the sodium charge to melt, 2) the distillation pot was evacuated, 3) after the volume of sodium was molten, the valves were manipulated to allow the sodium to be driven, by argon gas pressure, from the calibrated volume to the distillation pot, 4) the heaters extending from the distillation pot to the heat pipe were brought to temperature to allow sodium distillation into the evacuated heat pipe. Wet-in was accomplished by uniformly heating the heat pipe in a vacuum furnace at a temperature of 975 K for a period of approximately 48 hours.

TEST PROCEDURE AND RESULTS

The heat pipe was placed in a vacuum chamber in fully extended configuration. The circular portion of the evaporator was placed inside an rf induction coil as shown in Fig.5. Heat pipe operation at a temperature of 800 K was achieved by increasing the power input, in small increments, until the thermal melt front propagated from the evaporator to the end of the condenser. The power was then shut down and the system allowed to cool. The heat pipe was then removed from the vacuum chamber and the radiator element was rolled to a diameter of approximately 20 cm, and placed into the vacuum chamber in a fashion similar to the previous operation. Power input to the evaporator was increased in small increments. As operating conditions were approached the thermal front propagated from the evaporator to the rolled radiator portion and deployment began in a smooth continuous fashion. The extended portion of the radiator assumed a cylindrical configuration as shown in the photographs during

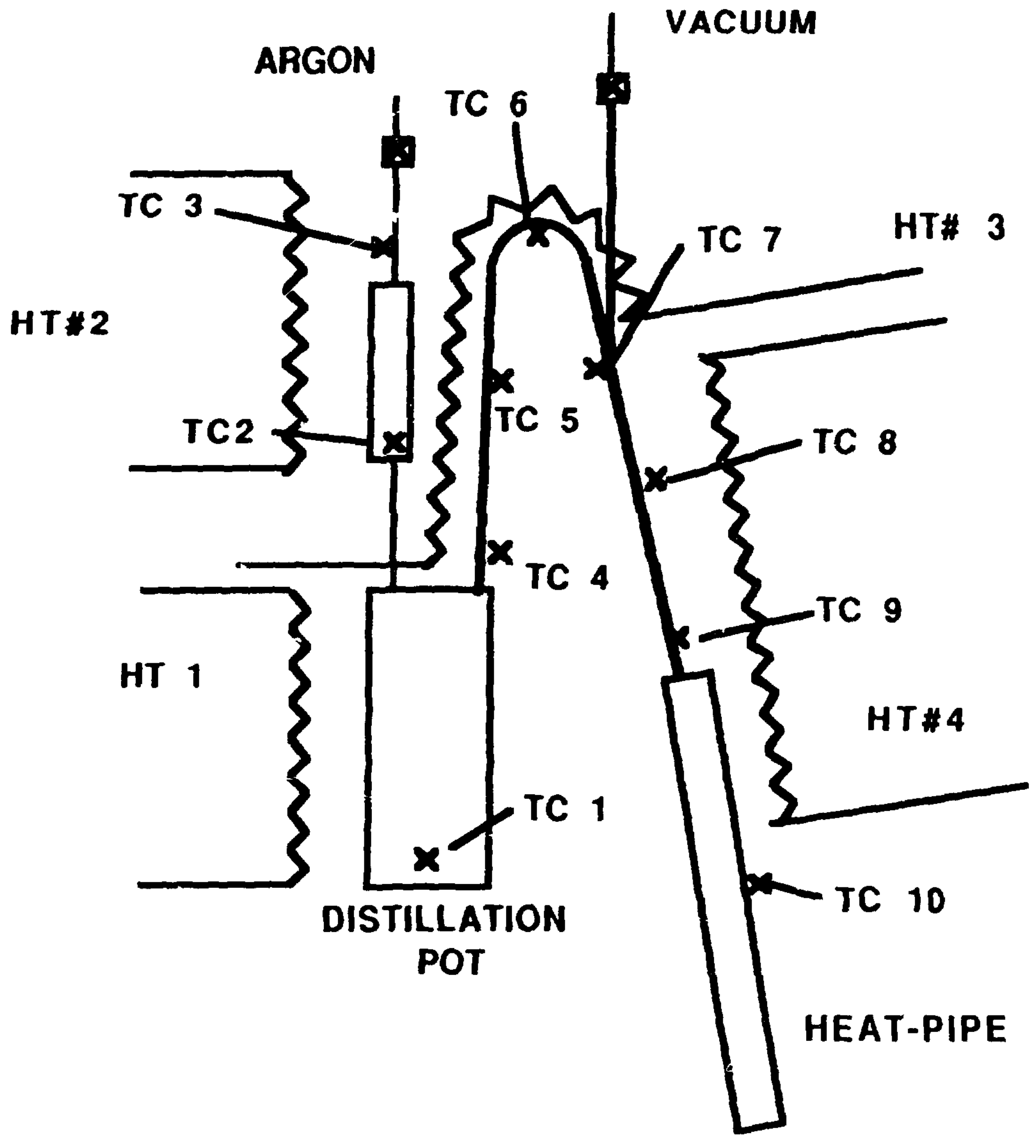

Figure 3: Schematic of set-up used to distill sodium into the heat-pipe.

Figure 4: Photograph of membrane heat pipe during distillation

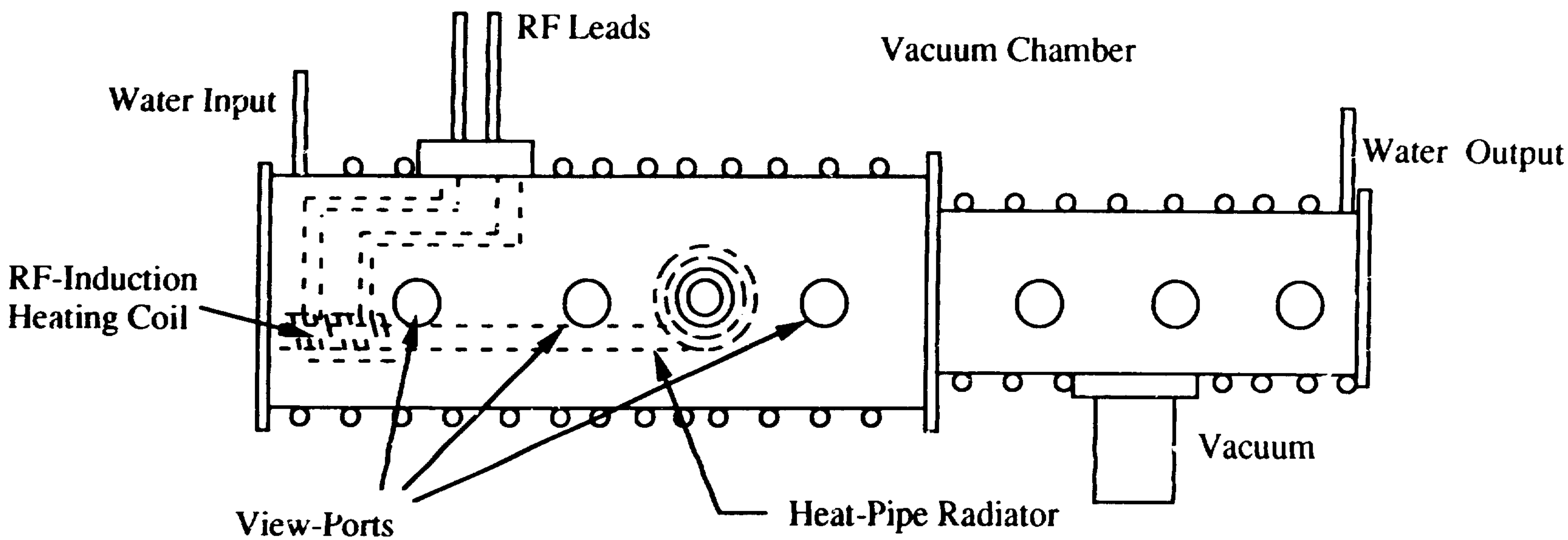

Figure 5: Schematic of the water-cooled vacuum chamber.

operation in Fig.6. Deployment began at a temperature of 700 K and was completely extended at 800 K. Tests were conducted at a peak temperature of 1000 K. Smooth deployment of the membrane radiator may be attributed to the melting of the sodium bond along the propagating thermal front. In addition the foil becomes more ductile in the heated region allowing the internal pressure of the fluid to expand the foil sheets. At peak power the radiator element was dissipating approximately 3.0 kW to the environment. Power dissipation was determined from radiative transport between two diffuse concentric cylinders [6] as in

$$Q=\sigma A_{hp}(T_{hp}^4-T_{vc}^4)/[1/\varepsilon_{hp}+(A_{hp}/A_{vc})(1/\varepsilon_{vc}-1)] \qquad (1)$$

where the subscripts hp and vc refer to the heat-pipe and vacuum chamber respectively.

There were no start-up anomalies apparent in the tests. Deployable heat pipes offer the advantage of effectively having a low L/D aspect ratio when initially in a rolled position so generally smooth start-up was expected. After full deployment of the membrane radiator the system assumed normal heat pipe operation in steady-state conditions.

PLANS FOR FUTURE WORK

The focus of this study was the demonstration of passive deployment for a single segment, high-temperature membrane heat-pipe. In practical designs several individual units may be joined together to form a segmented array as shown in Fig.1. A multi-segment, deployable, high-temperature, membrane heat pipe radiator is currently being investigated. The system will be capable of dissipating 20 kW of thermal power and consist of three segments with overall dimensions of 30 cm wide and 183 cm long. Heat input will be provided by rf induction heating. Metal foil for containment and an alkali metal as the working fluid will be utilized.

Analyses have shown that for the given geometry and power level in a microgravity environment, the fluid mass flow requirement can be satisfied with an artery/slab-wick combination for the fluid distribution system. The slab wick will be made of layers of 100X100 mesh stainless steel screen cut on the bias to allow for flexibility. Arteries will be formed by folding the ends of the slab wick and joining the lap to itself by resistance welding, as shown in Fig.7. A stainless steel cylindrical helix will be inserted into the artery to assure artery flexibility and prevent the artery walls from collapsing when the membrane-radiator is rolled.

Containment for the membrane radiator will consist of metal foil such as stainless steel or nickel. Metal foils for radiator containment as thin as 0.0025 cm are being investigated. The artery/slab-wick fluid distribution system will be joined to the metal foil by resistance welding and the foil sheets will be joined by seam welding along the edges to form the radiator envelope. Because the extended portion of the radiator tends to assume a cylindrical configuration, the foil adjacent to the seam weld experiences an abrupt bend and is subject to large stresses.

Figure 6: Photograph of membrane heat-pipe during operation a)evaporator/condenser transition region, b)transition of oblong to circular cross-section c)view form behind the evaporator with extended condenser d)side view of circular condenser

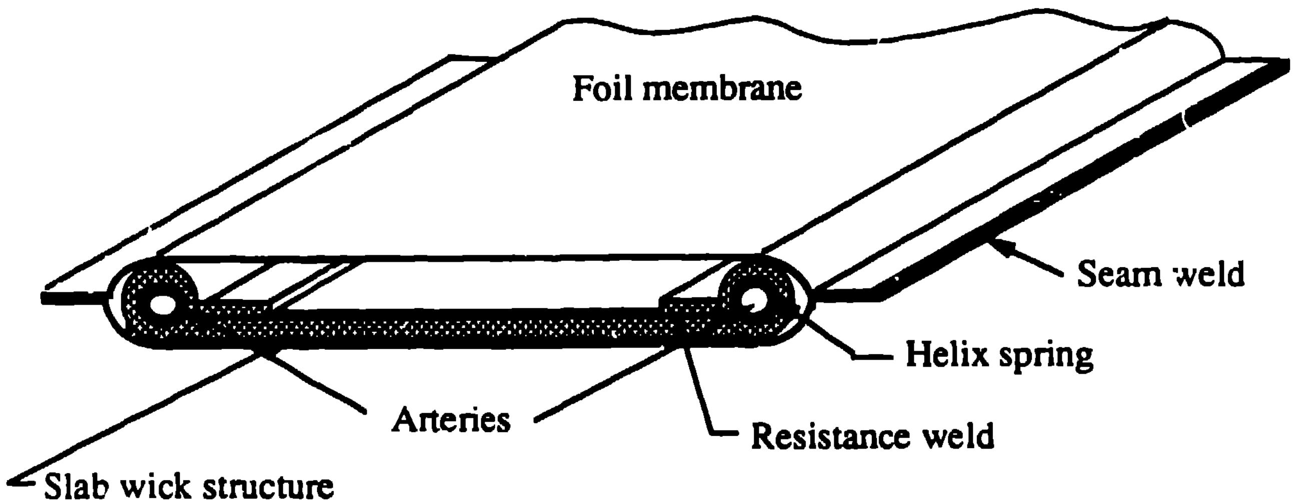

Figure 7: Cross-section of a single segment membrane radiator with flexible arteries.

Alternative weld closure configurations are under investigation to reduce the weld stresses.

Joining the radiator envelope to the thicker evaporator wall will be accomplished by a combination of resistance and fusion welding. The evaporator will have a constant cross section configuration with semi-cylindrical ends. This will allow for a smoother transition from the rigid evaporator to the flexible radiator and thus reduce the amount of wrinkling. A wire cage type structure will be placed in the evaporator/condenser cross-section interface to prevent the foil from being drawn into the evaporator during evacuation of the heat pipe chamber. The testing procedure will be similar to that of the single segment radiator element described in this paper.

CONCLUSION

Passive deployment has been demonstrated for a single segment, stainless steel, membrane, heat-pipe radiator element, at a temperature of 800 K. The tests showed that the radiator element deployed in a continuous, uniform manner. Upon full deployment of the membrane radiator the system assumed normal heat pipe operation in steady-state conditions at temperatures up to 1000 K. The tests indicate that operation of a full-scale, segmented model is achievable.

Membrane heat-pipe designs, utilizing alkali metals as the working fluids and metal foil for containment, offer the potential for a specific mass of about 1.8 kg/m^2 and a mass-to-power ratio of approximately 0.04 kg/kW at 1000 K.

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